. DTIC FILE COPY

(4)

AD-A197 372

AD________________

REPORT NO. T16/88

PHYSIOLOGICAL STRAIN DURING EXERCISE-HEAT STRESS EXPERIENCED BY SOLDIERS WEARING CANDIDATE CHEMICAL PROTECTIVE FABRIC SYSTEMS

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

JUNE 1988

Approved for public release distribution unlimited

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

TECHNICAL REPORT

Physiological Strain During Exercise-Heat Stress Experienced by Soldiers Wearing Candidate Chemical Protective Fabric Systems

C. Bruce Wenger and William R. Santee

U.S. Army Research Institute of Environmental Medicine

Natick, MA 01760-5007

June 1988

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION U.S. Army Res Inst of Env Med; 6b. OFFICE SYMBOL (If applicable) SGRD-UE-MEP	7a. NAME OF MONITORING ORGANIZATION U.S. Army Res Inst of Env Med
6c. ADDRESS (City, State, and ZIP Code) Kansas St. Natick, MS 01760-5007	7b. ADDRESS (City, State, and ZIP Code) Kansas St. Natick, MA 01760-5007
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Same as 6.a.; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) Same as 6.c.	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. –; PROJECT NO. –; TASK NO. 879 (Reimbursable funds); WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) Physiological strain during exercise-heat stress experienced by soldiers wearing candidate chemical protective fabric systems

12. PERSONAL AUTHOR(S)
C. Bruce Wenger and William R. Santee

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical Report	FROM ______ TO ______	June 1988	42

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Heat Tolerance, MOPP II, MOPP IV

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

(U) Five subjects each attempted 12 125-min heat exposures on different days, in three environments and wearing, in MOPP IV configuration, chemical protective uniforms made of four different fabric systems, viz. the current issue (84), and three candidate fabric systems, Monopak (MO), Bipak (BI), and a material made by Minnesota Mining and Manufacturing Co. (3M). Each heat exposure consisted of 10 min rest followed by four 25-min walks repeated by 5-min rest periods. Each subject walked on a level treadmill at a speed (1.34 $m \cdot s^{-1}$ or 1.56 $m \cdot s^{-1}$) chosen to elicit from him a metabolic rate of about 500W. The environments were all 29.5°C (85°F) dry bulb, at one of three combinations of relative humidity and wind speed: 1) 20%, 5 $m \cdot s^{-1}$ (11 mph); 2) 20%, 1.1 $m \cdot s^{-1}$ (2.5 mph); and 3) 85%, 5 $m \cdot s^{-1}$. Physiological responses used as indices of heat strain were heart rate (HR), rectal temperature (T_{re}), weighted 3-point mean skin temperature (T_{sk}), and change in rectal temperature since the start of exercise (ΔT_{re}). At the end of the fourth walk, the ranking of the uniforms from best to worst in terms of these indices of heat strain was MO, BI, 84, 3M.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT XX UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL C. Bruce Wenger, M.D., Ph.D.	22b. TELEPHONE (Include Area Code) 617-651-4837; 22c. OFFICE SYMBOL SGRD-UE-MEP

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. Abstract (cont'd)

However, of the physiological indices only ΔT_{re} and T_{sk} showed statistically significant differences ($P < 0.05$) between fabric systems, and the only significant ($P < 0.05$) pairwise comparisons between uniforms were that these indices were lower in MO than in either 84 or 3M.

To produce data for use in prediction modelling, all four fabric systems were also tested in MOPP II configuration, jacket closed, in environment 2. Physiological strain at the end of the fourth walk was significantly ($P < 0.05$) less in MOPP II configuration than in MOPP IV. Averaged across uniforms, T_{re} was 0.7°C lower, ΔT_{re} 0.8° lower, T_{sk} 2.0°C lower, and HR 30 min^{-1} lower in MOPP II.

MO, BI, and 3M, which are designed to be washed, were all tested again in environment 2 after washing. Washing the BI uniforms substantially and consistently reduced all indices of thermal strain. These improvements with washing were not quite statistically significant, but this is likely due to the small sample size. The non-durable fire retardant treatment, which does not withstand washing, may have been responsible for the greater heat strain in unwashed BI. If the BI fabric system is to undergo further evaluation, we recommend copper mannikin and/or human studies comparing thermal properties of that fabric system with and without fire retardant, to determine the trade-off between heat strain and fire protection.

The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other official documentation.

Human subjects participated in these studies after giving their informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Five subjects each attempted 12 125-min heat exposures on different days, in three environments and wearing, in MOPP IV configuration, chemical protective uniforms made of four different fabric systems, viz. the current issue (84), and three candidate fabric systems, Monopak (MO), Bipak (BI), and a material made by Minnesota Mining and Manufacturing Co. (3M). Each heat exposure consisted of 10 min rest followed by four 25-min walks separated by 5-min rest periods. Each subject walked on a level treadmill at a speed (1.34 $m \cdot s^{-1}$ or 1.56 $m \cdot s^{-1}$) chosen to elicit from him a metabolic rate of about 500W. The environments were all 29.5°C (85°F) dry bulb, at one of three combinations of relative humidity and wind speed: 1) 20%, 5 $m \cdot s^{-1}$ (11 mph); 2) 20%, 1.1 $m \cdot s^{-1}$ (2.5 mph); and 3) 85%, 5 $m \cdot s^{-1}$. Physiological responses used as indices of heat strain were heart rate (HR), rectal temperature (T_{re}), weighted 3-point mean skin temperature (T_{sk}), and change in rectal temperature since the start of exercise (ΔT_{re}). At the end of the fourth walk, the ranking of the uniforms from best to worst in terms of these indices of heat strain was MO, BI, 84, 3M. However, of the physiological indices only ΔT_{re} and T_{sk} showed statistically significant differences ($P<0.05$) between fabric systems, and the only significant ($P<0.05$) pairwise comparisons between uniforms were that these indices were lower in MO than in either 84 or 3M.

To produce data for use in prediction modelling, all four fabric systems were also tested in MOPP II configuration, jacket closed, in environment 2. Physiological strain at the end of the fourth walk was significantly ($P<0.05$) less in MOPP II configuration than in MOPP IV. Averaged across uniforms, T_{re}

was 0.7^{o}C lower, ΔT_{re} 0.8^{o}C lower, T_{sk} 2.0^{o}C lower, and HR 30 b•min^{-1} lower in MOPP II.

MO, BI, and 3M, which are designed to be washed, were all tested again in environment 2 after washing. Washing the BI uniforms substantially and consistently reduced all indices of thermal strain. These improvements with washing were not quite statistically significant, but this is likely due to the small sample size. The non-durable fire retardant treatment, which does not withstand washing, may have been responsible for the greater heat strain in unwashed BI. If the BI fabric system is to undergo further evaluation, we recommend copper mannikin and/or human studies comparing thermal properties of that fabric system with and without fire retardant, to determine the trade-off between heat strain and fire protection.

INTRODUCTION

The heat stress problem of soldiers working in warm environments wearing chemical protective clothing is well documented (1, 3-8). The thermal insulation and low moisture permeability of such clothing severely limit the effectiveness of the body's heat dissipating mechanisms. Several foreign and domestic experimental fabric systems are now available, and the thermal and vapor transfer characteristics of some of these systems have been tested in static configurations (Table 1). This technical report describes the evaluation of three experimental fabric systems for their effect on thermal strain experienced by soldiers during exercise in the heat.

For comparing experimental fabric systems with the current system, a Marine Corps draft criterion document calls for a 10% smaller increase in core temperature in soldiers exposed to heat while in full chemical protective ensemble, and the Army also has a goal of a 10% reduction in thermal strain, but neither criterion specifies the environment or exercise intensity to which this reduction applies. Individual Protection Directorate, NATICK, has asked USARIEM to conduct the present study, in order to compare the physiological strain experienced by soldiers wearing various chemical protective fabric systems during exercise-heat stress.

METHODS

Eight physically fit male soldiers volunteered and signed a statement of informed consent, after being informed of the purpose, procedures and risks of

Table 1. Thermal characteristics of fabric systems.

1. 7 oz/yd^2 Nyco,[a] quarpel, camouflage + 90 mil foam Type III (present chemical protective overgarment) "84"

- weight, 16.4 oz/yd^2
- air permeability, 9.3 cfm
- aluminum mannikin: I_t^b = 1.48 Clo; i_m^c = 0.28; i_m/I_t = 0.189/Clo

2. 7 oz/yd^2 Nyco, quarpel, camouflage laminated to carbon spheres on polyester taffeta "MO" (Monopak)

- Weight, 16.1 oz/yd^2
- air permeability, 8.5 cfm
- aluminum mannikin: I_t = 1.18 Clo; i_m = 0.26 i_m/I_t = 0.220/Clo

3. 7 oz/yd^2 Nyco, quarpel, camouflage FR[d] (nondurable) plus cotton knit laminated to carbon spheres on FR cotton. (This fabric system is being considered by the Marine Corps.) "BI" (Bipak)

- weight, 24.0 oz/yd^2
- air permeability, 8.9 cfm
- aluminum mannikin, I_t = 1.36 Clo; i_m = 0.30 i_m/I_t = 0.221/Clo

4. 5 oz/yd^2 Nyco (untreated) laminated to Goretex II laminated to polypropylene web with active carbon particles laminated to nylon tricot "3M"

- weight, 13.8 oz/yd^2
- air permeability, <1 cfm
- aluminum mannikin: I_t = 1.26 Clo; i_m = 0.33; i_m/I_t = 0.262/Clo

5. 70/30 modacrylic/nylon shell fabric plus napped polyester knit laminated to carbon knit fabric laminated to polyester tricot (Toyobo)

- weight, 14.4 oz/yd^2
- air permeability, 46.0 cfm
- aluminum mannikin: I_t = 1.37 Clo; i_m = 0.30 i_m/I_t = 0.219/Clo

[a] a nylon-cotton weave

[b] total insulation, i.e., the sum of intrinsic insulation and insulation of the boundary air layer. (1 Clo = $0.155 m^2 \cdot {}^oK \cdot W^{-1}$)

[c] Woodcock's water vapor permeability constant, no dimensions. i_m/I_t represents the ease of vapor permeation with respect to thermal resistance of the garment.

[d] fire retardant

the study, and their right to terminate participation at will without penalty; and they underwent a complete history and physical examination, including 12-lead resting EKG, in order to exclude the likelihood of conditions in which exercise and heat stress would impose significantly increased risk. Six of these volunteers (Table 2) served as test subjects. The other two volunteers were dismissed early in the study because of foot problems which did not respond satisfactorily to medical treatment and which caused the subjects to withdraw early from several experiments. Furthermore, to protect their feet those two volunteers sometimes adopted an unnatural gait, which required irregular and unusually high metabolic rates.

Table 2. Physical characteristics of subjects.

Subject	Height, cm	Weight, kg	DuBois Surface Area, m^2	Age, years
1	180	79.0	1.99	21
2	169	85.6	1.96	25
3	173	112.5	2.24	22
4	160	65.7	1.69	19
5	177	73.8	1.90	23
6	175	74.4	1.89	24
mean	172.3	81.8	1.945	22.3
SD	7.1	16.4	.179	2.2

All acclimation and testing were conducted in the tropic chamber at the U.S. Army Natick Research, Development and Engineering Center, Natick, Massachusetts. Test volunteers were heat acclimated for eight consecutive mornings, including one weekend. On each acclimation day, they attempted a two-hour heat exposure in a 35°C dry bulb, 75% rh (29.9°C dewpoint)

environment with 1.1 $m \cdot s^{-1}$ wind speed. They wore shorts, T-shirts, socks and athletic shoes. During the heat exposures, subjects rested for 10 min and walked on a treadmill at 1.56 $m \cdot s^{-1}$ (3.5 mph) on a 5% incline for 50 min each hour. Also, on the fifth afternoon during this week subjects practiced walking on the treadmill in the chemical protective clothing, but without mask and hood, in a cool environment. On that afternoon, we measured metabolic rates at different treadmill speeds to allow us to choose the treadmill speeds for the test days.

On the test days (Table 3), each subject walked on a level treadmill at a speed of either 1.34 or 1.56 $m \cdot s^{-1}$ (3 or 3.5 mph), chosen to elicit a metabolic rate of about 500 W. Each test day consisted of a 125-min heat exposure in 29.5°C (85°F) dry bulb, at one of three combinations of relative humidity and wind speed: 1) 20%, 5 $m \cdot s^{-1}$ (11 mph); 2) 20%, 1.1 $m \cdot s^{-1}$ (2.5 mph); and 3) 85%, 5 $m \cdot s^{-1}$. These environments were chosen so that differences in physiological strain between environments 1 and 3 would reflect predominantly differences in movement of water vapor, and differences in strain between environments 1 and 2 would reflect predominantly differences in convection and in air movement through the protective clothing.

Solar radiation is another factor affecting thermal strain. The tropic chamber has only infrared lamps to provide radiant heating. All clothing systems are likely to have emissivities near 1 in the infrared, and so are not likely to differ in their performance under radiative heat stress in the chamber. Since the chamber is not equipped to simulate the shorter wave length portion of the solar spectrum, that potential source of variation among the fabric systems could not

be evaluated in the tropic chamber, but can be evaluated in field tests.

Table 3. Study schedule

DAY		Environmental Conditions
	Acclimation[1]	
1-8		35°C, 75% rh, 1.1 $m \cdot s^{-1}$
	Test	
	Clothing Configuration	
9,14,17,18	MOPP IV	29.5°C, 20% rh, 5 $m \cdot s^{-1}$
11,12,15,16		29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$
10[2],13,19[3],21,23,25		29.5°C, 85% rh, 5 $m \cdot s^{-1}$
20	MOPP II	29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$
22,24,26	MOPP IV, washed	29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$

[1] On the afternoon of day 5 of the acclimation period, subjects walked on a level treadmill, dressed in chemical protective clothing, in a cool (20-22°C) environment. Subjects' oxygen consumption rates were measured at different treadmill speeds.

[2] This experiment was aborted, because of problems with the mask caused by the high humidity.

[3] Chamber temperature fell substantially below 29.5°C during the third walk on this day.

Subjects underwent 14 days of testing (including two makeup days) in order to evaluate four fabric systems (1-4 in Table 1), unwashed, in MOPP IV configuration in each of three environments. MOPP IV included overgarment, overboots, M17A1 mask with hood, and gloves. (After the second test day, we removed the outflow valves from the masks, to allow subjects to inhale through the outflow port, bypassing the intake valves and filters. We did this because in the high humidity condition, the intake valves often stuck and some subjects also complained of an ammoniacal smell and eye irritation, which presumably came from an ingredient in the filters.) The overgarments were worn over shorts and

T-shirt, in order to minimize variability in thermal characteristics of the total clothing ensemble, since we felt that bunching and binding of a uniform under the overgarments was likely to increase such variability. Wearing the overgarment directly over underwear is allowed at the commander's discretion (US Army STP 21-1-SBIT, 1985.) The order of presentation of the fabric systems was systematically varied in a counterbalanced design.

In addition, one test day was used to test the MOPP II (overgarment with jacket closed and overboots, but no mask, hood, or gloves) configuration. Different subjects wore different fabric systems on that day, so that all fabric systems were tested in MOPP II configuration. Another three test days were used to test washed uniforms, for comparison with the same uniforms before washing. All fabric systems that were intended to be washed (MO, BI, and 3M) were tested on those three days. Washed uniforms made of the Toyobo material (5, Table 1) were available, and were tested on the two subjects whose size was available in that material. Tests of MOPP II configuration and washed uniforms were all done at 29.5°C, 20% rh, and 1.1 $m \cdot s^{-1}$ wind speed (environment 2), since results of tests done in MOPP IV configuration suggested that that environment discriminated best among the different fabric systems.

During all heat exposures, rectal temperature (T_{re}) was measured with a thermistor inserted approximately 10 cm beyond the anal sphincter. The electrocardiogram was obtained from chest electrodes (CM5 placement) and displayed on an oscilloscope and cardiotachometer unit. On the test days, we

also measured skin temperatures on the chest, calf, and forearm with thermocouples, and used these temperatures to compute a mean skin temperature (T_{sk}), with chest, calf, and forearm temperatures weighted 50%, 36%, and 14%, respectively. Subjects drank ad libitum from weighed canteens, and water consumed by a subject during each walk was calculated from the change in weight of his canteen. Subjects were encouraged to drink cool water, to minimize dehydration. Pre- and post- exposure nude weights and water intake were measured and used to calculate total body sweating. About 15 min into each walk, we collected two minutes' expired air in Douglas bags, through fittings attached to the outflow valves of the masks, to measure oxygen consumption. Once during the study, expired air was also collected during the initial rest period, and once during a recovery period. Oxygen consumptions calculated from these collections were used along with those calculated for the walks to estimate total heat production during an experiment.

During each walk, subjects rated their feelings of heat (1 = cold, 4 = neutral, 7 = hot), discomfort (1 = not at all uncomfortable, 4 = very uncomfortable), and fatigue (1 = not at all tired, 4 = very tired).

Differences between uniforms in the physiological responses were tested for significance by one-way (uniform, taking one environment at a time) and two-way (uniform × environment) analysis of variance with repeated measures (using each subject as his own control). In addition, if analysis of variance did not show statistically significant differences in change in rectal temperature (ΔT_{re}), which is roughly proportional to heat storage, the data were re-analyzed by analysis of covariance, with metabolic rate as the covariate. Whenever there was a

significant F-ratio ($P<0.05$), pair-wise comparisons between uniforms were tested for significance by Tukey's t-test. Differences between uniforms in the sensory responses were analyzed by non-parametric statistics. Differences between washed and unwashed uniforms, and between MOPP II and MOPP IV were analyzed by paired t-tests.

Minimizing Risks to Subjects

All of the procedures in this study fell within the USARIEM Type Protocols for Human Research Studies of Exercise and Physical Training, and Human Research Studies of Thermal Stress (March, 1984), and all limits of thermal exposure listed in these Type Protocols were adhered to. A subject stopped exercise and was removed from the tropic chamber if his T_{re} reached 39.5°C, his heart rate exceeded 180 $b \cdot min^{-1}$ for five consecutive minutes, or he looked or felt faint, sick, or unable to continue.

RESULTS

Table 4 shows each subject's endurance time in each uniform and each environment. Subject 6 injured his knee in a road race early during the study. He completed the study, but frequently had to step off the treadmill because of pain in his injured knee. Since stepping off the treadmill affected his metabolic rate and heat production, his responses were not included in the statistical analysis of the physiological and psychophysical data (Tables 4-7 and A1-A10). Subject 1 developed sinusitis during the latter past of the study, and could not participate beginning on test day 11 (day 19 of the study). Although he recovered before the end of the study, we thought that the likelihood that he had

Table 4. Endurance time, min., unwashed uniforms, MOPP IV.

Environment 1 ($29.5^{o}C$, 20% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	125	125	93	125
2	125	125	125	125
3	125	125	125	125
4	125	125	125	125
5	125	125	125	125
mean	125	125	118.6	125
SD			14.31	

Environment 2 ($29.5^{o}C$, 20% rh, 1.1 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	125	125	105	125
2	125	125	125	125
3	125	125	125	125
4	125	125	125	125
5	121	125	125	115
mean	124.2	125	121	123
SD	1.79		8.94	4.47

Environment 3 ($29.5^{o}C$, 85% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	65	125	95	125.*	
3	125.*	125	97	65	101
4	71	125	71	111	
5	65	105	87	87	
mean	81.5	120	87.5	97	
SD	29.14	10.0	11.82	26.48	

Because of the work-rest cycle, endurance is not a continuous function.

* Poor control of chamber temperature, test day 11.

lost a substantial amount of his heat acclimatization was sufficient to raise questions about the validity of comparing any further data that we might collect on him with his earlier data. He thus participated in only two of the experiments in environment 3 (of which the first was aborted--see Table 3) and did not participate in the washed uniform and MOPP II experiments and the make-up experiments. Since the first experiment in environment 3 was aborted, it was not possible to use any of his data to compare different uniforms in environment 3.

During most of the third walk and the beginning of the fourth walk on test day 11, the temperatures in the tropic chamber fell substantially below the selected levels. Dry bulb temperature reached a low of 26.7°C, and was below 28°C for 20 min and below 29°C for 42 min. Dew point reached a low of 22.9°C, and was below 25°C for 42 min. (Target values of dry bulb and dew point temperatures were 29.5 and 26.6°C, respectively.) The subjects thus experienced less environmental stress (and probably also less physiological strain) than usual for environment 3. During the make-up days, two subjects were retested in the same uniforms and same conditions as on test day 11. For the other two, however, the responses on day 11 are presented in Tables 4 and A1-A7, and marked with an asterisk.

Effect of Environment

Endurance time in environment 3 was significantly ($P<0.05$) shorter than in environments 1 and 2. At the end of the second walk, differences among the three environments were statistically significant for HR, T_{sk}, and ΔT_{re}, and these responses were least in environment 1 and greatest in environment 3. At the end

of the fourth walk, differences between environments 1 and 2 were statistically significant for T_{sk} and ΔT_{re}, but not for HR.

Unwashed Uniforms, MOPP IV

The time course of T_{re} during the experiments is illustrated in Figs. 1-3, which show the effects of different fabric systems and environments on heat strain. Figure 1 shows T_{re} averaged across all subjects for each fabric system in environment 2, which gave the best discrimination among uniforms; Figure 2 shows T_{re} for subject 4 in each fabric system in environment 2; and Figure 3 shows T_{re} for subject 4 in the MO and 84 fabric systems in environments 1 and 3. In general, subjects came close to thermal steady state only in those combinations of environment and fabric system that produced the milder degrees of heat strain.

Endurance time of subjects wearing unwashed uniforms in MOPP IV configuration is shown in Table 4. Their physiological and perceptual responses are summarized in Table 5, and are listed more completely in Tables A1-A10 in the Appendix. Responses of Subject 3 wearing the washed Toyobo uniform in environment 3 are shown in the Appendix for information, but were not included in any statistical analyses.

Differences among uniforms in endurance time (Table 4), metabolic rate (Tables 5 and A1), T_{re} at the end of the third (Tables 5 and A2) and fourth walks, heart rate (Tables 5, A6, and A7), drinking (Tables 5 and A8) and sweat loss (Tables 5 and A9) were not statistically significant. Differences among uniforms in ΔT_{re} during the first three walks (Tables 5 and A3) for environments

MEAN RECTAL TEMPERATURES

5 SUBJECTS, ENVIRONMENT 2

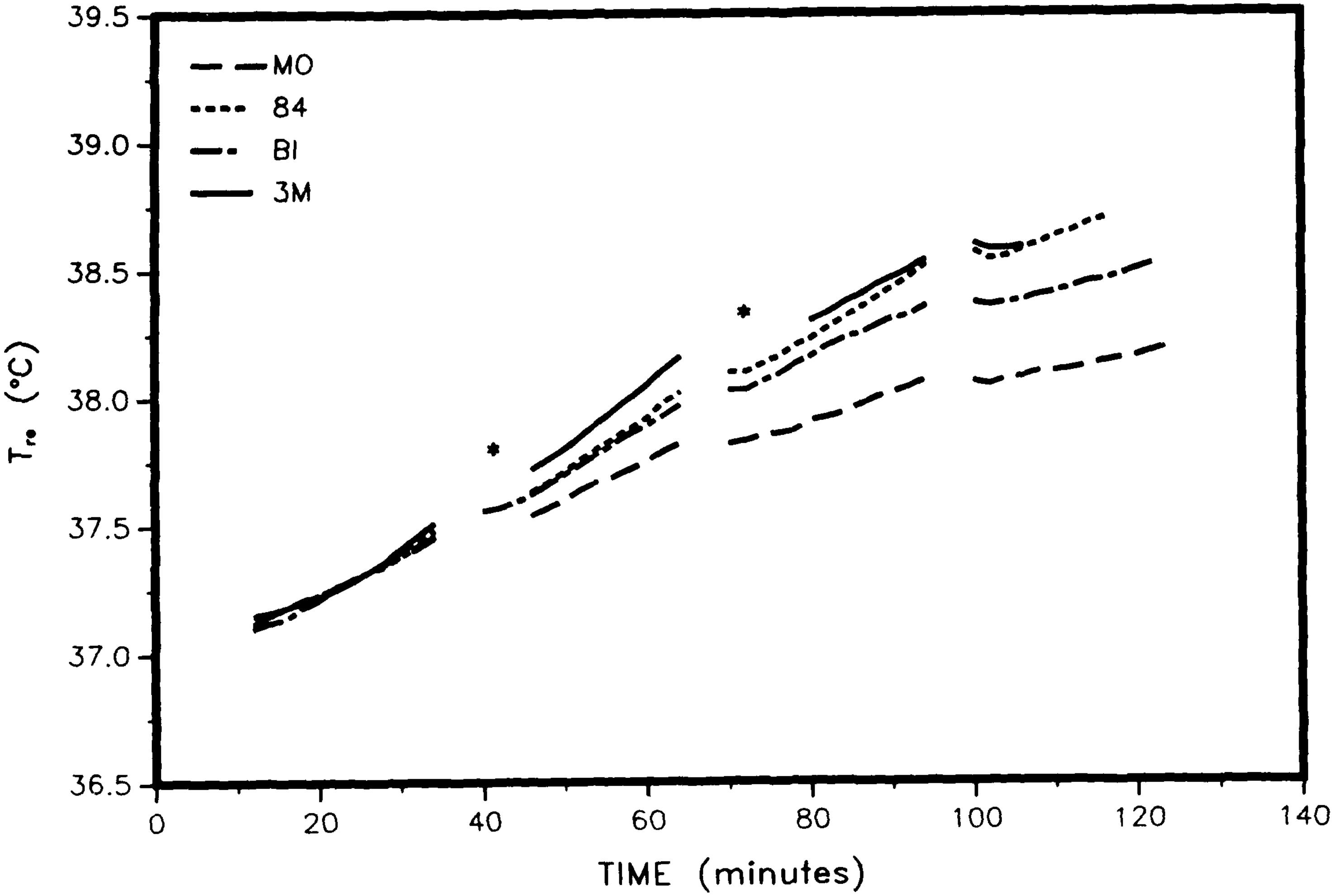

Figure 1.

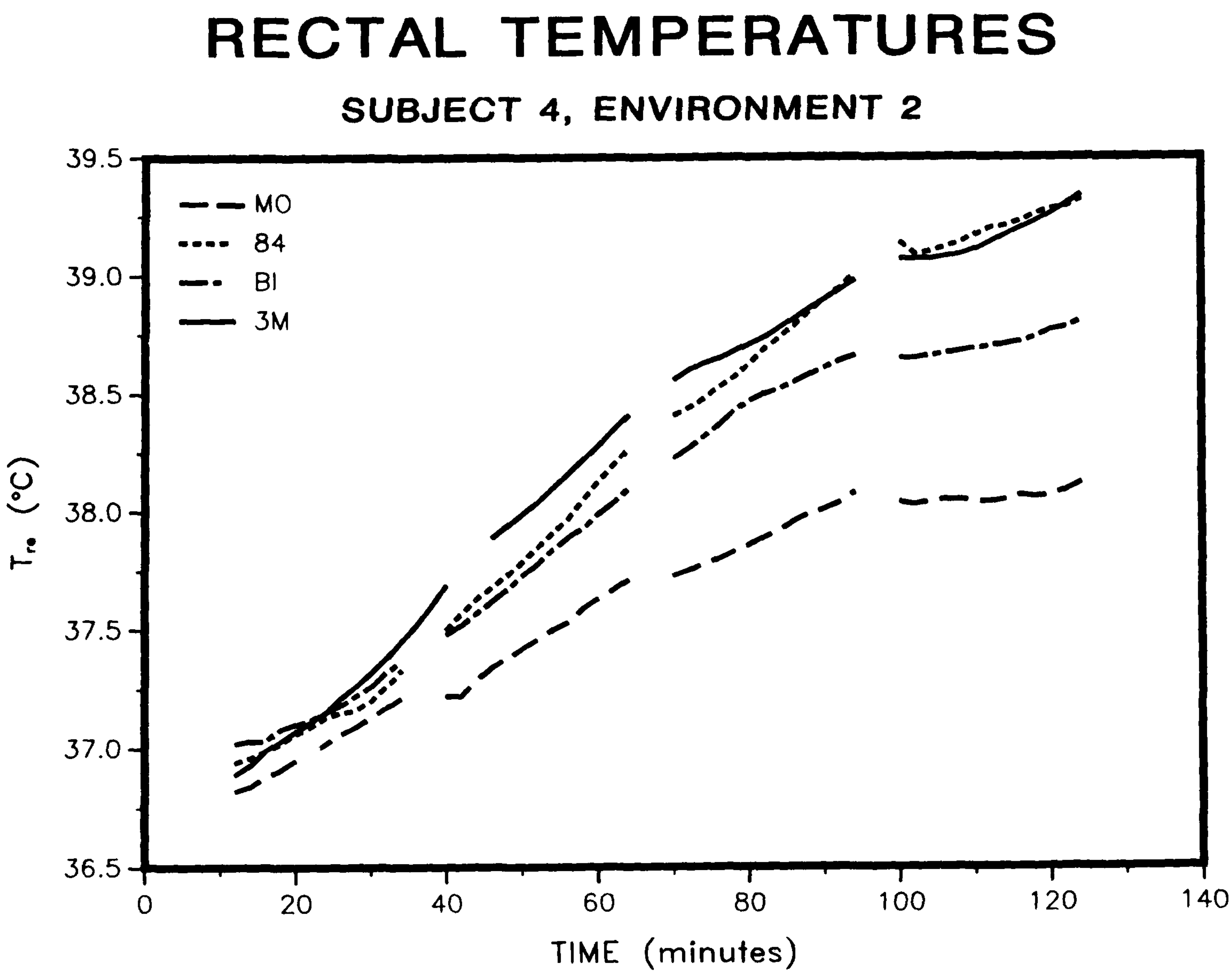
RECTAL TEMPERATURES
SUBJECT 4, ENVIRONMENT 2
MO
84
BI
3M
39.5
39.0
38.5
38.0
37.5
37.0
36.5
T_{re} (°C)
0
20
40
60
80
100
120
140
TIME (minutes)

Figure 2.

RECTAL TEMPERATURES

SUBJECT 4

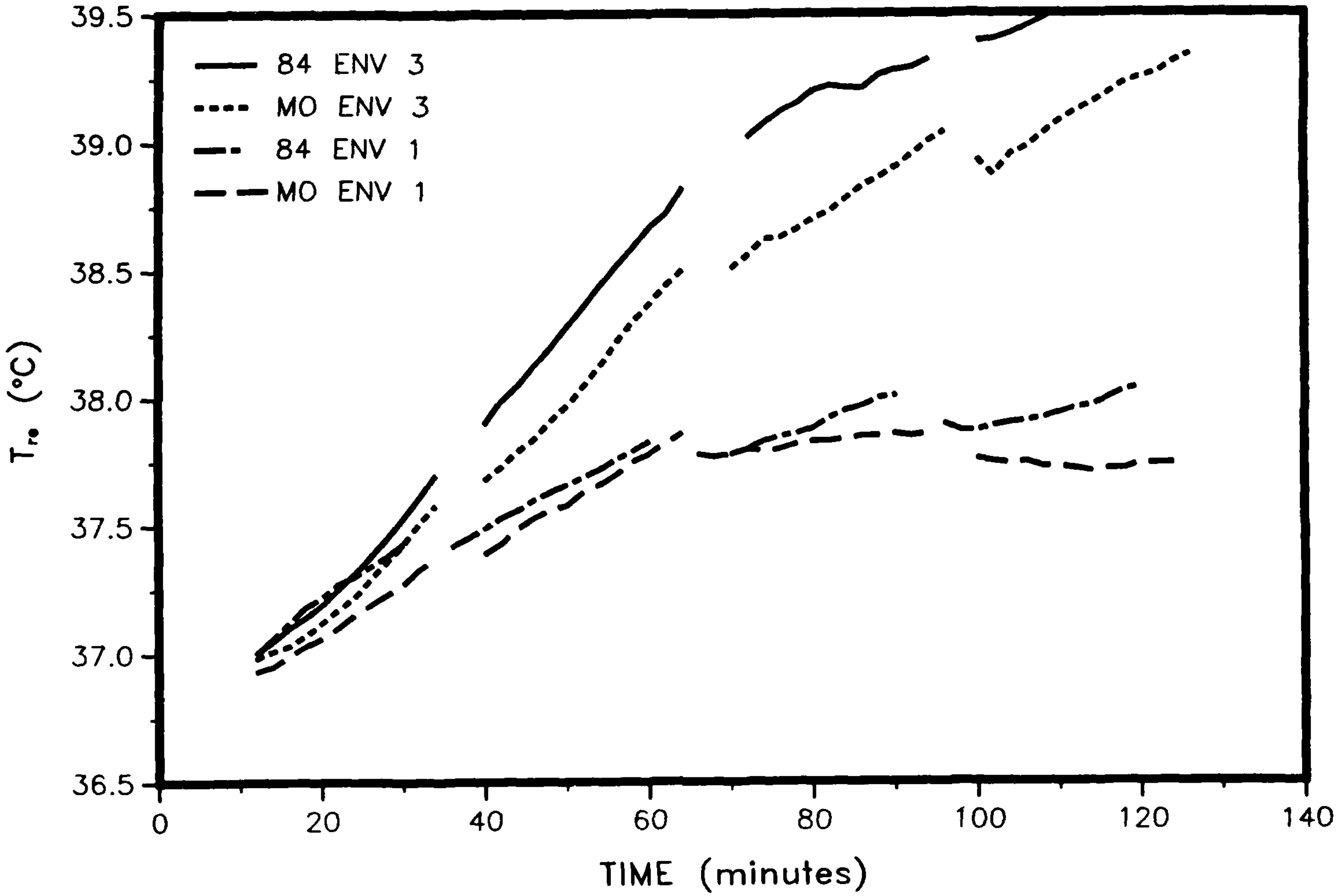

Figure 3.

Table 5. Summary data on subjects wearing different fabric systems, unwashed, in MOPP IV configuration.

Metabolic rate, $W \bullet M^{-2}$.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	262.8	267.2	266.2	268.6
29.5°C, 20% rh, 5 $m \bullet s^{-1}$	SE	18.5	13.1	17.0	11.2
Environment 2	mean	261.0	266.2	266.0	270.2
29.5°C, 20% rh, 1.1 $m \bullet s^{-1}$	SE	14.1	11.0	14.5	13.7
Environment 3	mean	280.2	290.2	266.8	275.5
29.5°C, 85% rh, 5 $m \bullet s^{-1}$	SE	15.5	11.7	9.2	12.9

Rectal temperature, T_{re}, °C, end of third walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	37.97	37.83	38.33	38.05
	SE	0.18	0.17	0.23	0.10
Environment 2	mean	38.38	38.07	38.54	38.52
	SE	0.21	0.14	0.18	0.19
Environment 3	mean	38.72	38.91	38.59	39.01
	SE	n=1	0.20	0.13	0.32

ΔT_{re}, °C, from start of experiment to end of third walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	0.74	0.75	1.07	0.88
	SE	0.17	0.11	0.26	0.16
Environment 2	mean	1.27	0.93	1.40	1.37
	SE	0.15	0.13	0.25	0.24
Environment 3	mean	1.32	1.80	1.38	1.87
	SE	n=1	0.20	0.03	0.51

ΔT_{re}, °C, from start of experiment to end of fourth walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	0.77	0.74	1.30	0.95
	SE	0.18	0.10	0.27	0.16
Environment 2	mean	1.43	1.07	1.79	1.63
	SE	0.19	0.17	0.30	0.26
Environment 3	mean	1.47	1.95		1.62
	SE	n=1	0.25		n=1

Mean skin temperature, °C, end of fourth walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	34.55	34.06	35.10	34.68
	SE	0.46	0.47	0.56	0.14
Environment 2	mean	35.63	34.81	36.47	36.29
	SE	0.55	0.31	0.50	0.36
Environment 3	mean	36.43	36.05		35.63
	SE	n=1	0.47		n=1

Heart rate, $b \bullet min^{-1}$, end of third walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	132	132.8	137	135.2
	SE	10.5	9.3	11.8	6.0
Environment 2	mean	140.3	141.3	140.8	152.3
	SE	9.7	8.4	8.9	9.6
Environment 3	mean	151.5	161	130.5	151.3
	SE	n=1	9.2	4.0	7.8

Heart rate, $b \bullet min^{-1}$, end of fourth walk.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	137.5	132.5	144.1	143.5
	SE	12.3	8.8	9.6	5.6
Environment 2	mean	147.5	143.2	151	156.3
	SE	12.8	9.2	8.7	7.9
Environment 3	mean	159.5	165		154
	SE	n=1	3.9		n=1

Water consumption, liters, total for four walks.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	1.72	1.43	1.77	1.82
	SE	0.19	0.14	0.22	0.10
Environment 2	mean	1.81	1.83	2.13	2.17
	SE	0.21	0.16	0.21	0.20

Sweat secreted, liters, total for four walks.

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	2.63	2.24	2.84	2.64
	SE	0.16	0.09	0.20	0.09
Environment 2	mean	3.16	2.74	3.21	3.12
	SE	0.16	0.13	0.18	0.24

Subjective ratings of sensory perceptions, third walk.

A. Heat (1=cold, 4=neutral, 7=hot)

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	4.8	4.9	5.4	4.8
	SE	0.49	0.84	0.55	0.49
Environment 2	mean	5.3	5	5.6	6
	SE	0.49	0.42	0.68	0.71

B. Discomfort (on a scale of 1-4).

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	1.7	1.8	2.3	1.9
	SE	0.27	0.38	0.58	0.40
Environment 2	mean	2.2	1.8	2.3	2.6
	SE	0.49	0.34	0.43	0.50

C. Fatigue (on a scale of 1-4).

	UNIFORM	BI	MO	3M	'84
Environment 1	mean	2.1	1.8	2.1	1.5
	SE	0.33	0.38	0.46	0.32
Environment 2	mean	1.7	1.6	2.4	2.4
	SE	0.43	0.25	0.40	0.63

1 and 2 combined were significant only when analyzed with metabolic rate as a covariate, and pair-wise comparisons of uniforms were not significant. Differences among uniforms in ΔT_{re} during all four walks (Tables 5 and A4) for environments 1 and 2 combined were highly significant ($P<0.005$), and ΔT_{re} in MO was significantly less than in 3M and 84. Differences among uniforms in T_{sk} at the end of the fourth walk (Tables 5 and A5) for environments 1 and 2 combined and for environment 2 alone were highly significant ($P<0.005$), and T_{sk} in MO was significantly lower than in 3M and 84. Since too few subjects finished the third and fourth walks in environment 3 to permit statistical analysis of data pooled from all environments, we also analyzed pooled data from all environments at the end of the second walk. Differences among uniforms in ΔT_{re} during the first two walks for 3 environments combined were significant ($P=0.027$), and ΔT_{re} in MO was significantly less than in 3M. There were no statistically significant interactions between uniform and environment.

Tables 5 and A10 list the subjects' perceptual responses during the third work bout for environments 1 and 2. No data are presented for environment 3 because few subjects were able to remain in the chamber to complete the questionnaire. The 3M overgarment was supplied in a solid olive drab color, whereas the BI, MO, and 84 overgarments were furnished in a woodland camouflage pattern. Subjects 2 and 3, who belong to the Chemical Corps and had considerably more experience with several chemical protective uniforms, tended to favor the 3M suit subjectively. The latter two subjects also had the greatest body mass. The subjects also very quickly perceived that the humid environment 3 was the most difficult, although problems with mask filters and breathing on the second test day (study day 10) may have contributed to that perception.

Non-parametric tests of the sensory responses showed no significant difference between uniforms.

Washed Uniforms

Responses of subjects wearing washed uniforms are presented in Table 6, together with the responses of the same subjects wearing the corresponding unwashed uniforms. Although these trends are not statistically significant, in subjects wearing the BI fabric system T_{re}, ΔT_{re}, and T_{sk} are consistently lower in the washed than in the unwashed uniforms.

MOPP II

Responses of subjects dressed in MOPP II configuration are presented in Table 7, together with responses of the same subjects wearing the same uniforms in MOPP IV configuration. Since the MOPP II configuration was tested with jacket closed, the differences in heat exchange between MOPP II and MOPP IV are entirely due to heat loss from head and neck. (It is possible, however, that psychological factors contributed to these differences by affecting autonomic responses.) Each fabric system was tested in MOPP II configuration on one subject. Differences between MOPP II and MOPP IV in T_{re}, ΔT_{re}, T_{sk}, and heart rate are all statistically significant ($P<0.05$), but differences in metabolic rate and water consumption are not.

DISCUSSION

At the beginning of the study, we were supplied with data on the thermal properties of the fabric systems based on measurements made on flat plates and

Table 6. Comparison of physiological responses of individual subjects in unwashed (U) and washed (W) chemical protective uniforms, at 29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$ wind speed (environment 2). Temperatures and heart rates are at the end of the fourth walk except as noted. Metabolic rates are averages for each experiment. In addition, responses of subjects wearing washed Toyobo uniforms are provided for information.

Uniform	Subject, Uniform Condition	T_{re} °C	ΔT_{re} °C	T_{sk} °C	HR $b \cdot min^{-1}$	M $W \cdot m^{-2}$	Endurance min
BI	2 U	37.89	1.14	34.17	118	233	125
	2 W	37.63	0.52	33.71	114.5	242	125
	3 U	38.71	1.26	36.49	154	276	125
	3 W	38.58	0.92	34.66	148	233	125
	4[1] U	38.66	1.66	37.16	150	301	125
	4[1] W	38.36	1.55	36.81	137.5	297	101
	5 U	39.25	1.95	35.77	184.5	270	121
	5 W	38.34	0.97	35.11	149	263	125
U-W,	mean	0.40	0.51	0.82	14.4	11.2	5
	SE	0.17	0.19	0.34	7.2	11.1	6.4
MO	2 U	37.80	0.74	34.26	115.5	237	125
	2 W	37.85	0.45	32.79	115.5	255	125
	3 U	38.35	1.05	34.50	148.	248	125
	3 W	38.59	0.96	34.74	145.5	239	125
	4 U	38.12	1.27	36.00	144.5	275	125
	4 W	38.23	1.18	34.68	154	303	125
	5 U	38.87	1.60	34.79	172	300	125
	5 W	38.32	1.14	35.04	152	265	125
U-W,	mean	0.04	0.23	0.58	3.0	0.5	0
	SE	0.18	0.09	0.47	6.2	14.2	0
3M	4 U	39.34	2.44	37.04	158.5	301	125
	4 W	38.61	1.48	36.16	158	301	125
	5[1] U	38.96	1.80	35.98	165	281	125
	5[1] W	38.85	1.46	36.30	181.5	275	91
U-W,	mean	0.42	0.65	0.28	-8.0	-3	17
	SE	0.31	0.31	0.60	8.5	3	17
TO	2[2] W	37.76	0.64	33.99	112.5		73
	3 W	38.39	0.91	35.43	141		125

[1] Since the subject did not complete the fourth walk in both conditions, the conditions are compared at the end of the third walk.

[2] End of second walk

Table 7. Comparison of physiological responses for individual subjects in MOPP II (with jacket closed) and MOPP IV configuration, at 29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$ wind speed (environment 2). Temperatures and heart rates are at the end of the fourth walk.

Subject, Uniform condition		T_{re} °C	ΔT_{re} °C	T_{sk} °C	HR $b \cdot min^{-1}$	M $W \cdot m^{-2}$	Water drunk l
2	MOPP II	37.67	0.54	32.39	100.0	237	1.56
MO	MOPP IV	37.80	0.74	34.26	115.5	250	1.42
3	MOPP II	38.28	0.62	34.97	123.0	244	1.68
3M	MOPP IV	38.81	1.48	37.21	149.0	282	1.93
4	MOPP II	37.76	0.77	35.16	122.5	286	1.42
BI	MOPP IV	38.81	1.81	37.12	162.0	300	2.09
5	MOPP II	38.22	0.89	34.35	134.5	259	1.83
84	MOPP IV	39.24	2.07	36.12	174.5	276	1.37
MOPP IV - MOPPII							
	mean	0.68	0.82	1.96	30.3	21	0.08
	SE	0.22	0.22	0.10	5.9	6	0.24

on an aluminum mannikin. The flat-plate data were inconsistent, so we have made no use of them. The aluminum mannikin data also differed from some copper mannikin data obtained at USARIEM, but the difference can be at least partly explained by different air-flow characteristics in different environmental chambers, the use of different mannikins, and varying techniques of the operators. For example, the aluminum mannikin data presented in Table 1 were measured at a wind speed of 2.2 $m \cdot s^{-1}$, which was specifically requested for the test series (J. Giblo, personal communication), while the USARIEM copper mannikin is normally run with a wind speed of 0.3 $m \cdot s^{-1}$.

The aluminum mannikin data (Table 1) led us to expect that the different overgarment sets would vary significantly in the degree to which they impeded evaporative and convective heat transfer to the environment, and we were guided by these considerations in selecting our test environments. Convective heat exchange is a function of wind speed and the gradient between skin and air temperature. Evaporative heat exchange is a function of wind speed and the difference in water vapor pressure between the environment and saturation vapor pressure at skin temperature. At a constant ambient temperature and humidity, the more the air movement, the greater the potential for both convective and evaporative heat transfer. Therefore, an overgarment set with a lower insulation value and/or greater permeability to air should allow a greater heat loss to the environment at a relative high wind speed, but at a lower wind speed such an advantage would be reduced. An overgarment with a higher i_m (water vapor permeability) should allow more cooling at a low humidity, but that advantage would decline in a more humid environment. We selected test conditions that

would determinc whether the apparent advantages of the prototype overgarments, as indicated by the biophysical data, in fact resulted in significant physiological advantages to the wearer. The air temperature was controlled at a constant value of 29.5°C for all the test sessions. Two levels of relative humidity (20% and 85%) and two wind speeds (1.1 $m \bullet s^{-1}$ and 5 $m \bullet s^{-1}$) were selected. At 20% rh both wind speeds were tested, but at the higher humidity only the 5 $m \bullet s^{-1}$ wind speed was selected. The fourth possible combination, high humidity and low wind, where both convection and evaporative cooling difference between uniforms would be minimized, was not tested because it was least likely to demonstrate a significant difference, except relative dry thermal insulation (I_t), between the 4 overgarment sets.

Differences among the three environments in endurance (Table 4) and in HR, T_{sk}, and ΔT_{re} at the end of the second walk were statistically significant. Environment 2 had the same ambient temperature and humidity as environment 1, but a lower wind speed, while environment 3 had the same ambient temperature and wind speed as environment 1, but a higher humidity. The effect of environment can also be appreciated qualitatively from Figure 3, and from tabulated presentation of T_{re}, ΔT_{re}, T_{sk}, and HR in Table 5 and the Appendix. The effect of humidity (comparing environments 1 and 3) on physiological strain was roughly twice that of wind speed (comparing environments 1 and 2). It is particularly noteworthy that the effect of high ambient humidity on physiological strain of subjects clothed in these chemical protective suits is fairly large, even though their low moisture permeability seriously limits cooling by evaporation of sweat. Most subjects failed to complete all four work-rest cycles in environment

3 (Table 4). This failure indicates that for soldiers dressed in MOPP IV configuration in any of these fabric systems and exercising with 500 W heat production, two hours' exposure to conditions of 29°C, 5 m•s^{-1} wind speed, and 85% relative humidity is near or beyond the limit of toleration.

Based on all the physiological data, the overall ranking of the fabric systems, from coolest to warmest was MO, BI, 84, 3M. (Not all steps of this ranking, however, are equal or statistically significant.) This might seem somewhat surprising, since based on the aluminum mannikin data, the ranking by i_m/I_t is 3M, BI, MO, 84. However, the 3M fabric system has by far the lowest air permeability of any of the fabric systems studies (Table 1). Air movement through clothing is produced both by ambient air movement and by the subjects' movements, and it is likely low air permeability accounts for much of the physiological strain experienced by subjects wearing the 3M uniform. The BI and MO uniforms have nearly identical values for air permeability and i_m/I_t, and the physiological differences between them were never statistically significant. However, physical characteristics that were not measured, such as stiffness of the fabric systems or the ease with which they move over underwear and skin, could affect the "pumping" of air inside and through the overgarments, and thus their heat transfer properties. (This property of clothing ensembles is discussed and quantified as a "pumping coefficient" in ref. 2.)

The only physiologically significant routes of heat exchange between any mammal and the environment are through the skin and the respiratory tract, and in humans the skin is by far the more important. The primary thermal effect of

clothing is to alter heat exchange between the skin and the environment, and the effects on body heat storage and core temperature are consequences of this primary effect. Thus T_{sk} is the most direct index of the effects of clothing on the thermal state of the body, and will show these effects earlier than will core temperature. Final T_{sk} (Tables 5 and A5) in the various fabric systems has the same ranking as does ΔT_{re} (Tables 5 and A4).

Heat strain experienced by subjects wearing the BI fabric system was substantially less in washed than in unwashed uniforms (Table 6). Although these differences were not statistically significant for the four subjects tested, t-values for differences in T_{re}, ΔT_{re}, and T_{sk} all exceed 2.0, and these t-values would be large enough for statistical significance ($P<0.05$) with a larger sample size. The fire retardant on the BI fabric system does not withstand washing, and in fact, we frequently saw it being leached out by the subjects' sweat, and re-deposited on the surface of the uniform in patches that loc d like salt. Because of that observation, and also since the effect of washing on heat strain of subjects wearing the other fabric systems was much smaller (Table 6), it is likely that the fire retardant impairs the heat-dissipating abilities of the BI fabric system, although washing may have caused other changes also.

The difference in thermal strain experienced by test subjects wearing different fabric systems depends not only on the properties of the fabric systems themselves, but also on the environment, metabolic rate, and length of heat exposure used for testing. For example, comparison of values of ΔT_{re} at the end of the third walk (Tables 5 and A3) with those at the end of the fourth walk

(Tables 5 and A4) shows that an additional 30 min of heat exposure increases the difference in ΔT_{re} between BI and MO on the one hand, and 3M and 84 on the other, both absolutely and proportionally. Thus a criterion based on a particular difference in heat strain has no precise meaning unless the test conditions are specified. In principle it is possible to choose test conditions in which a relatively small difference in heat-dissipating properties of fabric systems will (within limits of physiological tolerance) produce a disproportionately large difference in heat strain. If the test conditions are chosen so that the metabolic heat production is within the maximum heat-dissipating power of the chosen environment with the better uniform for heat dissipation, a maximally sweating subject will eventually be able to reach thermal equilibrium. If, however, these same test conditions are such that the same metabolic heat production exceeds the maximum heat dissipating power of the same environment in the the worse uniform for heat dissipation, a subject wearing that uniform will never reach thermal equilibrium, and his core temperature will continue to rise until he can no longer maintain that rate of heat production. Therefore the heat transfer properties of the types of uniforms being compared are not sufficient to predict the difference in heat strain experienced by subjects wearing those different types of uniforms. It also is necessary to take into account the environmental heat stress and exercise demands imposed on the subjects and, if the subjects do not come into thermal balance, the duration of the stress.

SUMMARY

1. Five subjects each attempted 12 125-min heat exposures on different days, in three environments and wearing in MOPP IV configuration chemical protective

uniforms made of four different fabric systems, viz. the current issue (84), and three candidate fabric systems, Monopak (MO), Bipak (BI), and a material made by Minnesota Mining and Manufacturing Co. (3M). Each heat exposure consisted of 10 min rest followed by four 25-min treadmill walks, at a metabolic rate of about 500W, separated by 5-min rest periods. The environments were: 1) 29.5°C dry bulb, 20% relative humidity, and 5 $m \cdot s^{-1}$ wind speed; 2) 29.5°C, 20%, 1.1 $m \cdot s^{-1}$; and 3) 29.5°C, 85%, 5 $m \cdot s^{-1}$. At the end of the fourth walk, the overall ranking of the uniforms from best to worst in terms of heat strain, as indicated by heart rate (HR), rectal temperature (T_{re}), change in rectal temperature since the start of exercise (ΔT_{re}), and weighted 3-point mean skin temperature (T_{sk}) was MO, BI, 84, 3M; but only ΔT_{re} and T_{sk} showed statistically significant differences ($P<0.05$) between fabric systems, and the only significant ($P<0.05$) pairwise comparisons between uniforms were that these indices were lower in MO than in either 84 or 3M.

2. All four fabric systems were also tested in MOPP II configuration, jacket closed, in environment 2. Physiological strain at the end of the fourth walk was significantly ($P<0.05$) less in MOPP II configuration. Averaged across uniforms, T_{re} was 0.7°C lower, ΔT_{re} 0.8°C lower, T_{sk} 2.0°C lower, and HR 30 $b \cdot min^{-1}$ lower in MOPP II.

3. MO, BI, and 3M, which are designed to be washed, were tested again in environment 2 after washing. Washing the BI uniforms substantially and consistently reduced all indices of thermal strain, perhaps by removing the non-durable fire retardant treatment.

REFERENCES

1. Goldman, R. F. Tolerance time for work in the heat when wearing CBR protective clothing. Milit. Med. 128: 776-786, 1963.

2. Goldman, R. F. Clothing, its physiological effects, adequacy in extreme thermal environments, and possibility of future improvements. Arch. Sci. Physiol. 27: A137-A147, 1973.

3. Henane, R., J. Bittel, R. Viret, and S. Morino. Thermal strain resulting from protective clothing of an armored vehicle crew in warm conditions. Aviat. Space Environ. Med. 50: 599-603, 1979.

4. Joy, R. J. T., and R. F. Goldman. A method of relating physiology and military performance: A study of some effects of vapor barrier clothing in a hot climate. Milit. Med. 133: 458-470, 1968.

5. Tanaka, M., G. R. Brisson, and M. A. Volle. Body temperatures in relation to heart rate for workers wearing impermeable clothing in a hot environment. Am. Ind. Hyg. Assoc. J. 39: 885-890, 1978.

6. Terrian, D. M., and S. A. Nunneley. A laboratory comparison of portable cooling systems for workers exposed to two levels of heat stress. Technical Report No. USAFSAM-TR-83-14, USAF School of Aerospace Medicine, Brooks Air Force Base, TX 78235.

7. Toner, M. M., L. L. Drolet, C. A. Levell, L. Levine, L. A. Stroschein, M. N. Sawka, and K. B. Pandolf. Comparison of air shower and vest auxiliary cooling during simulated tank operations in the heat. Technical Report No. T2/83, US Army Research Institute of Environmental Medicine, Natick, MA 01760.

8. Toner, M. M., R. E. White, and R. F. Goldman. Thermal stress inside the XM-1 tank during operations in an NBC environment and its potential alleviation by auxiliary cooling. Technical Report No. T4/81, US Army Research Institute of Environmental Medicine, Natick, MA 01760.

APPENDIX

Table A1. Mean metabolic rate, $W \cdot m^{-2}$, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	212	232	216	232
2	230	255	236	257
3	290	254	288	272
4	312	302	305	294
5	270	293	286	288
mean	262.8	267.2	266.2	268.6
SD	41.4	29.3	38.1	25.0

Environment 2 (29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	225	237	220	242
2	233	248	246	243
3	276	275	282	275
4	301	300	301	317
5	270	271	281	274
mean	261.0	266.2	266.0	270.2
SD	31.6	24.6	32.5	30.7

Environment 3 (29.5°C, 85% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
2	253	258	251	248.*
3	261.*	295	252	261
4	321	314	288	305
5	289	294	276	288
mean	280.2	290.2	266.8	275.5
SD	31.0	23.4	18.3	25.8

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A2. Rectal temperature, °C, at end of third walk, unwashed uniforms MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	37.70	37.63	37.79	37.73
2	37.71	37.36	38.03	38.29
3	38.69	37.96	38.17	37.98
4	37.81	37.86	39.10	38.01
5	37.96	38.36	38.58	38.23
mean	37.97	37.83	38.33	38.05
SD	0.41	0.37	0.52	0.22

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	38.05	37.84	38.13	38.36
2	37.74	37.67	38.22	38.04
3	38.53	38.30	38.40	38.25
4	38.66	38.08	38.98	39.01
5	38.90	38.44	38.96	38.94
mean	38.38	38.07	38.54	38.52
SD	0.47	0.32	0.41	0.43

Environment 3 (29.5°C, 85% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	38.35	38.45	38.69*	
3	38.72*	38.98	38.73	--	38.53
4	--	39.04	--	39.32	
5	--	39.28	--	--	
mean	38.72	38.91	38.59	39.01	
SD		0.40	0.19	0.45	

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A3. ΔT_{re}, °C, from start of experiment to end of third walk, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	0.15	0.55	0.54	0.40
2	0.63	0.62	0.63	1.21
3	1.16	0.54	1.11	0.61
4	1.01	0.95	2.02	1.09
5	0.73	1.07	1.05	1.08
mean	0.74	0.75	1.07	0.88
SD	0.39	0.25	0.59	0.35

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	1.01	0.67	0.91	1.08
2	0.99	0.59	1.06	1.11
3	1.08	1.00	1.07	0.79
4	1.66	1.23	2.18	2.10
5	1.60	1.17	1.80	1.77
mean	1.27	0.93	1.40	1.37
SD	0.33	0.29	0.56	0.54

Environment 3 (29.5°C, 85% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	1.22	1.35	1.36*	
3	1.32*	1.73	1.40	--	0.94
4	--	2.10	--	2.38	
5	--	2.15	--	--	
mean	1.32	1.80	1.38	1.87	
SD		0.43	0.04	0.72	

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A4. ΔT_{re}, °C, from start of experiment to end of fourth walk, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	0.13	0.51	--	0.45
2	0.68	0.72	0.73	1.21
3	1.16	0.58	1.21	0.73
4	0.99	0.83	2.02	1.12
5	0.87	1.07	1.23	1.24
mean	0.77	0.74	1.30	0.95
SD	0.40	0.22	0.53	0.35

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	0.99	0.71	--	1.30
2	1.14	0.74	1.14	1.28
3	1.26	1.05	1.48	1.08
4	1.81	1.27	2.44	2.41
5	1.95	1.60	2.08	2.07
mean	1.43	1.07	1.79	1.63
SD	0.43	0.37	0.59	0.58

Environment 3 (29.5°C, 85% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	1.53	--	1.62*	
3	1.47*	1.92	--	--	--
4	--	2.40	--	--	
5	--	--	--	--	
mean	1.47	1.95		1.62	
SD		0.44			

* Poor control of chamber temperature, test day 11.

Table A5. Mean skin temperature, °C, at end of fourth walk (mean of last 3 readings), unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	34.20	34.38		34.24
2	33.55	33.20	34.07	34.56
3	36.24	34.68	34.81	34.89
4	34.06	32.77	36.68	35.03
5	34.72	35.26	34.83	34.70
mean	34.55	34.06	35.10	34.68
SD	1.03	1.04	1.11	0.32

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	34.59	34.49		36.78
2	34.17	34.26	35.04	34.95
3	36.49	34.50	37.21	36.72
4	37.12	36.00	37.04	36.89
5	35.77	34.79	36.58	36.12
mean	35.63	34.81	36.47	36.29
SD	1.24	0.69	0.99	0.81

Environment 3 (29.5°C, 85% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	35.14	--	35.63*	
3	36.43*	36.74	--	--	--
4	--	36.26	--	--	
5	--	--	--	--	
mean	36.43	36.05		35.63	
SD		0.82			

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A6. Heart rate, $b \bullet min^{-1}$, at end of third walk, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	107	118	100	116
2	108	108	125	134
3	149	132	136	132
4	138	146	160	141
5	158	160	164	153
mean	132	132.8	137	135.2
SD	23.5	20.9	26.3	13.5

Environment 2 (29.5°C, 20% rh, 1.1 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	120	141	120.5	123.5
2	114	112	126	146.5
3	157	142	134	144.5
4	150	147.5	158.5	171
5	160.5	164	165	176
mean	140.3	141.3	140.8	152.3
SD	21.7	18.8	19.9	21.4

Environment 3 (29.5°C, 85% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	136.5	126.5	143.5*	
3	151.5*	158.5	134.5	--	147
4	--	169.5	--	159	
5	--	179.5	--	--	
mean	151.5	161	130.5	151.3	
SD		18.4	5.7	11.0	

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A7. Heart rate, $b \bullet min^{-1}$, at end of fourth walk, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	110	109		123
2	112.5	118.5	121.5	144
3	173.5	130	139	145
4	136	140	148.5	149
5	155.5	164	167.5	156.5
mean	137.5	132.5	144.1	143.5
SD	27.4	19.6	19.1	12.5

Environment 2 (29.5°C, 20% rh, 1.1 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	119	136		135
2	118	115.5	128	145
3	154	148	149	153
4	162	144.5	158.5	174
5	184.5	172	168.5	174.5
mean	147.5	143.2	151	156.3
SD	28.7	20.5	17.3	17.6

Environment 3 (29.5°C, 85% rh, 5 $m \bullet s^{-1}$)

UNIFORM	BI	MO	3M	'84	TO
SUBJECT					
2	--	159.5	--	154.*	
3	159.5*	163	--	--	--
4	--	172.5	--	--	
5	--	--	--	--	
mean	159.5	165		154	
SD		6.7			

* Poor control of chamber temperature, test day 11.

APPENDIX

Table A8. Water consumption, liters, in four walks, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84	mean
SUBJECT					
1	1.33	1.79	1.41*	1.61	1.54
2	1.69	1.14	1.20	1.93	1.49
3	2.09	1.59	2.27	1.66	1.90
4	2.22	1.56	2.27	2.18	2.06
5	1.29	1.09	1.68	1.73	1.45
mean	1.72	1.43	1.77	1.82	1.68
SD	0.43	0.31	0.49	0.23	

Environment 2 (29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84	
SUBJECT					
1	1.82	2.04	1.50	2.22	1.90
2	2.34	1.42	2.52	1.84	2.03
3	1.67	1.91	1.93	2.60	2.03
4	2.09	2.24	2.63	2.83	2.45
5	1.14	1.52	2.08	1.37	1.53
mean	1.81	1.83	2.13	2.17	1.99
SD	0.46	0.35	0.46	0.59	

* $1\frac{1}{3}$ × consumption for 3 bouts.

APPENDIX

Table A9. Sweat secreted, liters, in four walks, unwashed uniforms, MOPP IV.

Environment 1 (29.5°C, 20% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84	mean
SUBJECT					
1	2.18	2.49	2.21[1]	2.51	2.35
2	2.39	2.04	2.55	2.53	2.38
3	3.09	2.39	3.17	2.46	2.78
4	2.87	2.06	3.25	2.88	2.77
5	2.64	2.24	3.03	2.83	2.64
mean	2.63	2.24	2.84	2.64	2.59
SD	0.36	0.20	0.45	0.20	

Environment 2 (29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84	
SUBJECT					
1	2.97	3.04	2.65[2]	----*	2.89
2	3.79	2.32	3.57	2.89	3.14
3	3.07	2.91	3.28	3.05	3.08
4	3.04	2.89	3.08	3.88	3.22
5	2.94[3]	2.52	3.48	2.67[4]	2.90
mean	3.16	2.74	3.21	3.12	3.05
SD	0.35	0.30	0.37	0.53	

* data lost
[1] for 93 min heat exposure
[2] for 105 min heat exposure
[3] for 121 min heat exposure
[4] for 115 min heat exposure

APPENDIX

Table A10. Subjective ratings of sensory perceptions, third walk, unwashed uniforms, MOPP IV.

A. Perception of heat (on a scale of 1-7, where 4 = neutral, 7 = hot)

Environment 1 (29.5°C, 20% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	4	6	7	5
2	4	4	4	5
3	4	2	4	3
4	6	6	6.5	6
5	6	6.5	5.5	5
mean	4.8	4.9	5.4	4.8
SD	1.10	1.88	1.24	1.10

Environment 2 (29.5°C, 20% rh, 1.1 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	5	5	7	6
2	5	4	4	--
3	4	4	4	4
4	7	6.5	7	7
5	5.5	5.5	6	7
mean	5.3	5	5.6	6
SD	1.10	0.95	1.52	1.41

B. Perception of discomfort (on a scale of 1-4).

Environment 1 (29.5°C, 20% rh, 5 $m \cdot s^{-1}$)

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	1	2	3	1
2	1	1	1	2
3	2	1	1	1
4	2	2	4*	3
5	2.5	3	2.5	2.5
mean	1.7	1.8	2.3	1.9
SD	0.60	0.84	1.30	0.89

APPENDIX

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	2	2	2	3
2	1	1	1	--
3	2	1	2	1
4	4	2.5	3.5	3
5	2	2.5	3	3.5
mean	2.2	1.8	2.3	2.6
SD	1.10	0.76	0.97	1.11

* discomfort due to improperly fitted boot

C. Perception of fatigue (on a scale of 1-4).

Environment 1 (29.5°C, 20% rh, 5 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	3	2	4	1
2	1	1	1	1
3	2	1	1	1
4	2	2	2.5	2
5	2.5	3	2	2.5
mean	2.1	1.8	2.1	1.5
SD	0.74	0.84	1.02	0.71

Environment 2 (29.5°C, 20% rh, 1.1 m•s^{-1})

UNIFORM	BI	MO	3M	'84
SUBJECT				
1	1	1	3	2
2	1	1	1	--
3	1	2	2	1
4	3	2	3	2.5
5	2.5	2	3	4
mean	1.7	1.6	2.4	2.4
SD	0.97	0.55	0.89	1.25

DISTRIBUTION LIST

2 Copies to:

Commander
U.S. Army Medical Research and Development Command
ATTN: SGRD-RMS
Fort Detrick
Frederick, MD 21701-5012

12 Copies to:

Defense Technical Information Center
ATTN: DTIC-DDA
Alexandria, VA 22304-6145

1 Copy to:

Commandant
U.S. Army Academy of Health Sciences
ATTN: AHS-COM
Fort Sam Houston, TX 78234

1 Copy to:

Director, Biological and Med Sciences Division
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

1 Copy to:

Commanding Officer
Naval Medical Research and Development Command
National Naval Medical Center
Bethesda, MD 20014

1 Copy to:

Commander
HQS, AFMSC/SGPA
Brooks Air Force Base, TX 78235

1 Copy to:

Director, Defense Research and Engineering
ATTN: Assistant Director (Environment and Life Sciences)
Washington, DC 20301

1 Copy to:

Dean
School of Medicine
Uniformed Services University of the Health Sciences
4301 Jones Bridge Road
Bethesda, MD 20814-4799

2 Copies to:

Commander
U.S. Army Medical Research Institute of Chemical Defense
Aberdeen Proving Ground, MD 21010-5425

2 Copies to:

Commander
U.S. Army Chemical Research, Development, and Engineering Center
Aberdeen Proving Ground, MD 21010-5423

2 Copies to:

Commandant
U.S. Army Chemical School
Fort McClellan, AL 38205-5000

2 Copies to:

Commander
U.S. Army Medical Research and Development Command
ATTN: SGRD-PLC
Fort Detrick
Frederick, MD 20701-5012

2 Copies to:

Commander
U.S. Army Medical Research and Development Command
ATTN: SGRD-PLE
Fort Detrick
Frederick, MD 20701-5012

2 Copies to:

Commander
U.S. Air Force School of Aerospace Medicine
Brooks Air Force Base, TX 78235

2 Copies to:

Commander
Naval Health Research Center
P.O. Box 85122
San Diego, CA 92138-9174

2 Copies to:

Commander
U.S. Army Biomedical Research and Development Laboratory
Fort Detrick
Frederick, MD 21701-5010

2 Copies to:

Commander
U.S. Army Medical Materiel Development Activity
Fort Detrick
Frederick, MD 21701-5009

2 Copies to:

Military Liaison Officer to DCIEM
1133 Sheppard Avenue W.
P.O. Box 2000
Downsview, Ontario
Canada M3M 3B9

2 Copies to:

Commander
U.S. Army Natick Research, Development and Engineering Center
ATTN: STRNC-Z
Natick, MA 01760-5000

4 Copies to:

Commander
U.S. Army Natick Research, Development and Engineering Center
ATTN: STRNC-IC
Natick, MA 01760-5000

2 Copies to:

Office of The Surgeon General
ATTN: DASG-PSP
5109 Leesburg Pike
Falls Church, VA 22041-3258

2 Copies to:

Under Secretary of Defense for Acquisition
ATTN: OUSDA (R&AT/E&LS)
Washington, DC 20310

2 copies to:

Commanding General
Marine Corps Research, Development, and Acquisition Command
ATTN: Firepower Division (D091)
Quantico, VA 22134